

Changes in soil hydraulic and physio-chemical properties under treated wastewater irrigation: A meta-analysis

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ABSTRACT

Treated wastewater (TWW) is increasingly used for irrigation, but its higher salt content compared to conventional water sources can induce soil salinization and sodification. This, in turn, may result in structural degradation and deterioration of soil hydraulic properties. The practice of using TWW for irrigation is not new, and it has long been applied in arid countries, with limited other water resources, while in recent years it is also getting used elsewhere given the worldwide influence on water resources. However, comparing and extrapolating results from existing studies on the use of TWW for irrigation is challenging due to the heterogeneity between experimental setups in terms of water quality, irrigation techniques applied, and pedo-climatic conditions. To explore the effect of TWW quality on soil hydraulic and physio-chemical following TWW irrigation and to examine to what extent these effects are soil type dependent, we compiled a database with results from 24 peer-reviewed studies across different soil types containing information on the link between TWW irrigation, and hydraulic and physio-chemical properties through various measurements. The meta-analysis revealed that application of TWW significantly increases sodium adsorption ratio (on average $71 \pm 6\%$) and electrical conductivity (on average $51 \pm 5\%$) of soil as compared to the use of conventional water source. Overall, there were no significant effects on the soil pore space (bulk density, soil total porosity) or pH. Interestingly, the application of TWW significantly increased soil organic carbon and aggregate stability, potentially even benefiting soil structure. In addition, the organic compounds in TWW also might lead to hydrophobicity. Yet, the effects of TWW on soil hydraulic and physio-chemical properties are not consistent across different TWW types and soil classes. A larger number of studies is required to draw sound conclusions on this topic. Anyway, this analysis already indicated that different soil textures might react differently to TWW irrigation. While in medium-textured soils, salt accumulation was observed and TWW significantly increased soil organic carbon and saturated hydraulic conductivity, fine-textured soils are more prone to clogging and reduced in saturated hydraulic conductivity. We also noticed an impact of the type of TWW, since the degree of treatment has a big impact on the remaining components added to the soils together with the water. Primary TWW, from which settleable and floatable solids are removed, resulted in the highest accumulation of salts and significantly increased soil organic carbon and improved soil aggregate stability. However, the elevated biochemical oxygen demand or chemical oxygen demand in this type of TWW leads to an accumulation of organic materials in the soil, negatively affecting its permeability and reducing soil saturated hydraulic conductivity. This study stresses the need for more standardized experiments quantifying the effect of TWW not only in terms of transfer of contaminants and biosafety, but also an effect on soil quality, and more specifically soil physical quality, especially at the longer term.

1. Introduction

The agricultural industry is the largest global water consumer and accounts for more than two-thirds of the world's water consumption

(Mekonnen and Hoekstra, 2016; United Nations, 2023). However, with a growing global population and the impact of climate change, freshwater resources are becoming increasingly limited (Vergine et al., 2017; Corcoran, 2010). To address this issue, numerous countries are investing

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in wastewater treatment and reuse (Vergine et al., 2017; Corcoran, 2010; Jones et al., 2021). Also the EU is now equipped with legislation safeguarding the safe use of treated wastewater (TWW) to irrigate crops, the Water Reuse Regulation. In agriculture, more than 10% of the global irrigated areas now utilize TWW (Zhang and Shen, 2019; Jiménez-Cisneros, 1995). However, it is essential to treat wastewater adequately before using it on agricultural land (Carey and Migliaccio, 2009). It has to undergo various treatment processes, resulting in primary TWW, secondary TWW, and tertiary TWW, as classified by FAO (Asano et al., 1987). Primary treatment focuses on the removal of settleable and floatable solids, as well as the reduction of incoming biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Asano et al., 1987). As the most widely used criteria for water quality assessment, BOD and COD provide information about the ready biodegradable fraction of the organic load in water (Jouanneau et al., 2014). The purpose of secondary treatment is to further treat the effluent from primary treatment in order to remove residual organic and suspended solids (Asano et al., 1987). To obtain tertiary TWW requires addition of chemical coagulants, often followed by filtration through sand activated carbon granular medium filters to remove nutrients and remaining suspended solids, refractory organics, heavy metals, and dissolved solids (Aquastat, 2010). Appropriate wastewater treatment is vital to obtain cost-friendly, but also safe water resources in addition to conventional freshwater resources.

However, despite the potential benefits of TWW irrigation in reducing freshwater pressure, its utilization may have adverse effects on soil quality due to the presence of various soluble salts, organic compounds or suspended solids. This can lead to soil contamination, salinization (Gao et al., 2021), and sodification (Levy et al., 2014), resulting in hydrophobicity (Asano et al., 1987; Leuther et al., 2018) and structure degradation (Levy et al., 2014). As a consequence, infiltration, hydraulic conductivity, and aggregate stability (AS) are adversely affected (Leuther et al., 2018; Asano et al., 1987; Assouline and Narkis, 2011; Schacht and Marschner, 2015). To assess the impacts of TWW irrigation on soil quality, various indicators have been used in the literature. Soil electrical conductivity (EC) represents soil salinity, while sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) are used to evaluate soil sodicity (Hopmans et al., 2021a, 2021b). Sodic soils contain high amounts of adsorbed sodium ions which cause the degradation of soil structure due to the dispersion of clay minerals. As a result, aeration and water movement is restricted within sodic soil. High sodium concentrations strongly affect soil pH by inducing high association of OH^- and decreased H^+ binding capacity at the exchange site, which consequently increase the soil pH (Okebalama and Marschner, 2023). This again determines the availability of nutrients and the solubility of ions, such as sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}). Both saline and sodic conditions considerably reduce the agricultural productivity of a soil.

However, as TWW often brings additional organic compounds, they can serve to stabilize soil aggregates, leading to improvements in soil total porosity (TP) (Cakmakci and Sahin, 2021), bulk density (BD), AS (Gharaibeh et al., 2016), hydraulic properties, and consequently water infiltration (Ibrahimi et al., 2022). Gharaibeh et al. (2016) reported that TWW irrigation resulted in a slight decrease in BD and an observable increase in aggregation percentage due to significant increase in soil organic carbon (SOC). Ibrahimi et al. (2022) reported that TWW application significantly increased the saturated hydraulic conductivity (Ks) compared to an adjacent non-irrigated control. It remains uncertain whether the benefits of TWW as a water and nutrient source outweigh the risk for deterioration of soil hydraulic characteristics in the longer term (Ibrahimi et al., 2022). However, it is clear that these effects are highly context-dependent, varying with soil type, climate, water source and treatment scheme.

In this study, we performed a meta-analysis, which is a set of statistical techniques to perform a quantitative analysis across multiple independent research data sets, which focus on the same topics or

purposes (Stanley and Jarrell, 2005). Statistically, meta-analyses reveal the overall effects and provide indication on the variability between studies and sometimes the contradictions among similar studies (Stanley and Jarrell, 2005). To our knowledge, there is no meta-analysis so far focusing on the effect of TWW irrigation on soil physical properties and hydrological functioning. Gao et al. (2021) conducted a global meta-analysis to assess the effects of irrigation on soil salinity, with subgroups based on TWW class according to FAO (Aquastat, 2010) and soil classifications. While their study indicated that TWW or salty water irrigation led to soil salinity, they did not consider soil sodicity or hydraulic properties. Cheng et al. (2021) carried out a meta-analysis to understand how water productivity and crop yield were affected by irrigation with salty water, but did not take into account soil properties. A recent synthesis of meta-analyses related to European agriculture revealed a lack of research on the effects of saline irrigation on soil pore space, hydraulic and mechanical properties, and water balance (Blanchy et al., 2022). It is important to quantify the effect of TWW quality and soil type on soil hydraulic and physio-chemical properties following TWW irrigation. In addition, an accurate estimate of the adverse effects is crucial to expose and mitigate potential long-term problems, especially now that practices including TWW as a water resource for agriculture are increasingly adopted. Therefore, we conducted a meta-analysis of 24 independent peer-reviewed studies across different TWW qualities and soil types to review the impact of TWW irrigation and quality on hydraulic and physio-chemical properties and to examine to what extent this impact is soil type dependent.

2. Materials and methods

2.1. Data collection

This meta-analysis followed the PRISMA 2020 guidelines, which provide a standard for reporting systematic reviews (Page et al., 2021). We established our database by conducting an automated, comprehensive search on Web of Science and Google Scholar. The query string was as follows: soil AND irrigation AND (reclaim* OR treated OR recycle OR reuse) AND (“waste water” OR effluent OR sewage OR wastewater) AND (hydr* OR structure OR quality OR physic* OR stability OR infiltration) AND (“aggregate stability” OR “bulk density” OR “hydraulic conductivity” OR “water repellency” OR infiltration). We focused on peer-reviewed English articles and searched for these terms within the title, abstract, and indexing fields. Truncation with asterisks (*) allowed for variations of the search terms: for example, reclaim* can contain reclaiming and reclaimed, and hydr* can involve hydrologic and hydraulic. We used quotation marks (“”) to ensure an exact phrase search.

After the initial search, the records obtained were further screened for relevance and quality. A flow chart detailing the paper selection criteria used in this meta-analysis is given in Fig. 1. Based on the information provided in the abstract and titles, studies that were deemed clearly irrelevant to our research objectives were excluded from further consideration. Further full-text article screening was conducted according to the specific objectives of this study. Firstly, only papers that involved experiments with both TWW irrigation (treated/reclaimed/recycled/reuse wastewater/effluent/sewage) and a qualified conventional irrigation water source (rainfall, fresh/spring/tap/drinking water irrigation) were selected, thus making the selection more focused. Secondly, only studies that contained data on soil structural properties and hydraulic properties were selected. Thirdly, as we were interested in the practical relevance of TWW irrigation in agriculture, we selected studies that were based on field irrigation experiments and excluded laboratory experiments. Finally, only articles containing at least one targeted indicator pair (for TWW irrigation and conventional irrigation) with mean, standard deviation or standard error, and the number of replicates being reported were selected. These selected articles formed the basis for further analysis and synthesis of the data.

Based on the remaining qualifying publications, eight representative

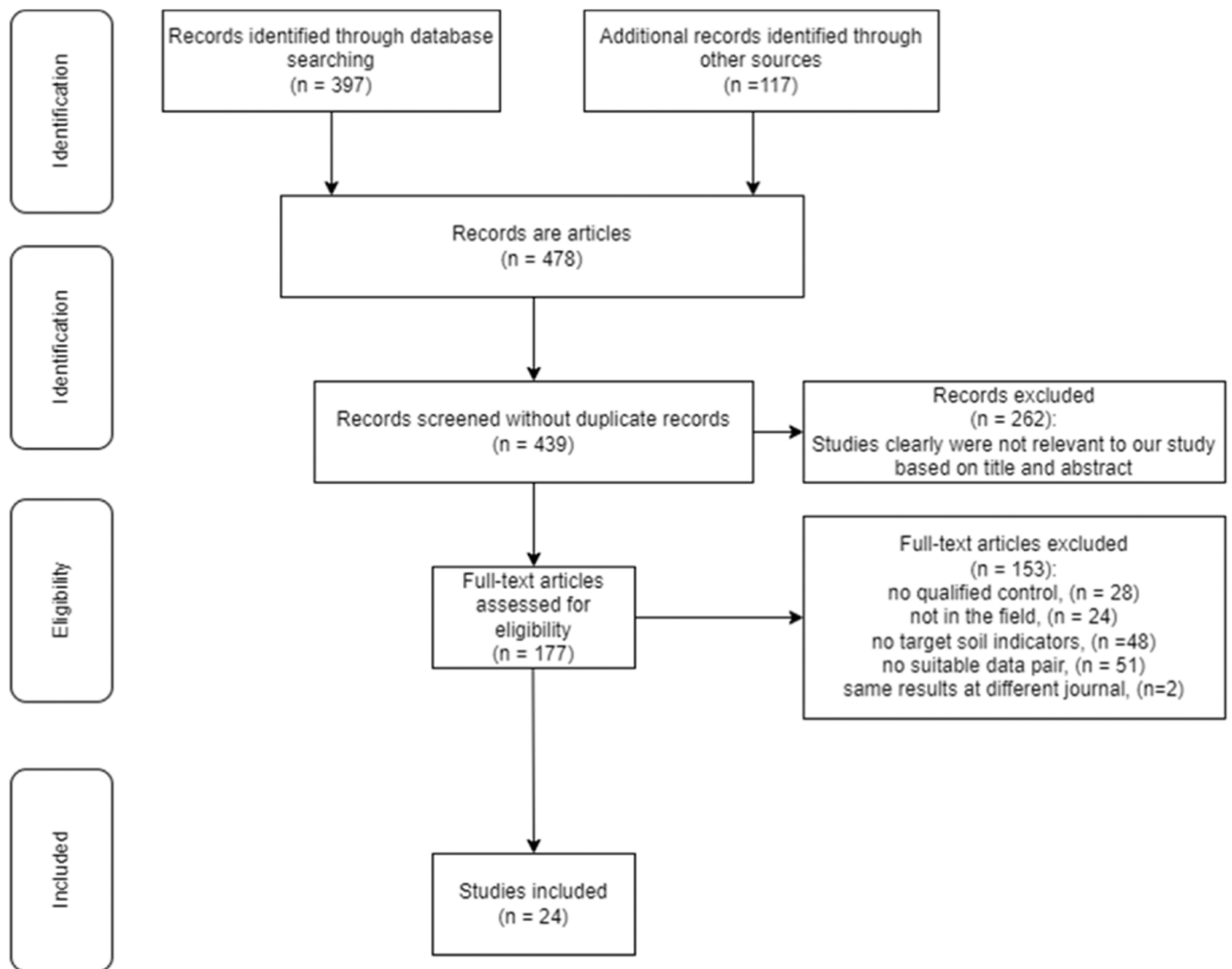


Fig. 1. Flow chart of publication selection for the meta-analysis following the PRISMA protocol.

soil indicators related to salinity and soil physical and chemical quality were selected for the meta-analysis: aggregate stability (AS), bulk density (BD), total porosity (TP), saturated hydraulic conductivity (Ks), soil organic carbon (SOC), soil pH, sodium adsorption ratio (SAR) and electrical conductivity (EC). Although many publications use the exchangeable sodium percentage (ESP) as an important indicator of soil sodicity, both SAR and ESP serve as representative indicators for this condition (Hopmans et al., 2021a, 2021b). Therefore, to avoid redundancy in our analysis, we chose to focus exclusively on SAR.

Indicators such as water drop penetration time, as an indication of water repellency, and CaCO_3 concentration (known to significantly influence soil pH after TWW irrigation), were excluded because they were measured in fewer than five publications. The infiltration rate was not included in the analysis due to the difficulty in obtaining the standard deviation or standard error for the infiltration rate curves and problems with intercomparison as stated in Blanchy et al. (2023). These statistical measures are essential for calculating the effect size, which is a crucial aspect of meta-analysis. The modified laser diffraction method was employed to measure AS in two studies, while in thirteen other studies, the wet sieving method was utilized. In all the retained articles, Ks was measured by the falling head method with undisturbed core samples in the laboratory (1 study), or constant head method in the laboratory (6 studies), or constant head method with double-ring infiltrometer in the

field (1 study). A saturated paste (5 studies), a 1:2 soil/water extract or a 1:5 soil/water extract/suspension (5 studies) was used to measure EC. Two studies measured soil pH with 1:2.5 suspension, while the others measured it on a saturation paste.

2.2. Data analysis

In this meta-analysis, each pair of data was treated as an independent observation. The number of observations for soil indicator is presented in Fig. 2. For instance, if a study included multiple irrigation methods, each irrigation method (e.g. surface irrigation, sprinkler irrigation, drip irrigation) was considered as a separate observation. It is worth noting that many studies determined the soil properties at variable soil depth, with a wide range of intervals. This study only focuses on the topsoil to ensure consistency and comparability across the selected studies. The majority of sampling depths considered in our study varied from 5 to 30 cm (see Appendix A). In cases where data from multiple years or periods were reported in the same study, the last year or period was selected to represent the maximum accumulated effect of TWW irrigation. The experiment duration of selected experiments thus varied from eight weeks to 50 years, as indicated in Appendix A.

Since both SAR and ESP serve as representative indicators for soil sodicity (Hopmans et al., 2021a, 2021b), we chose to exclusively explore

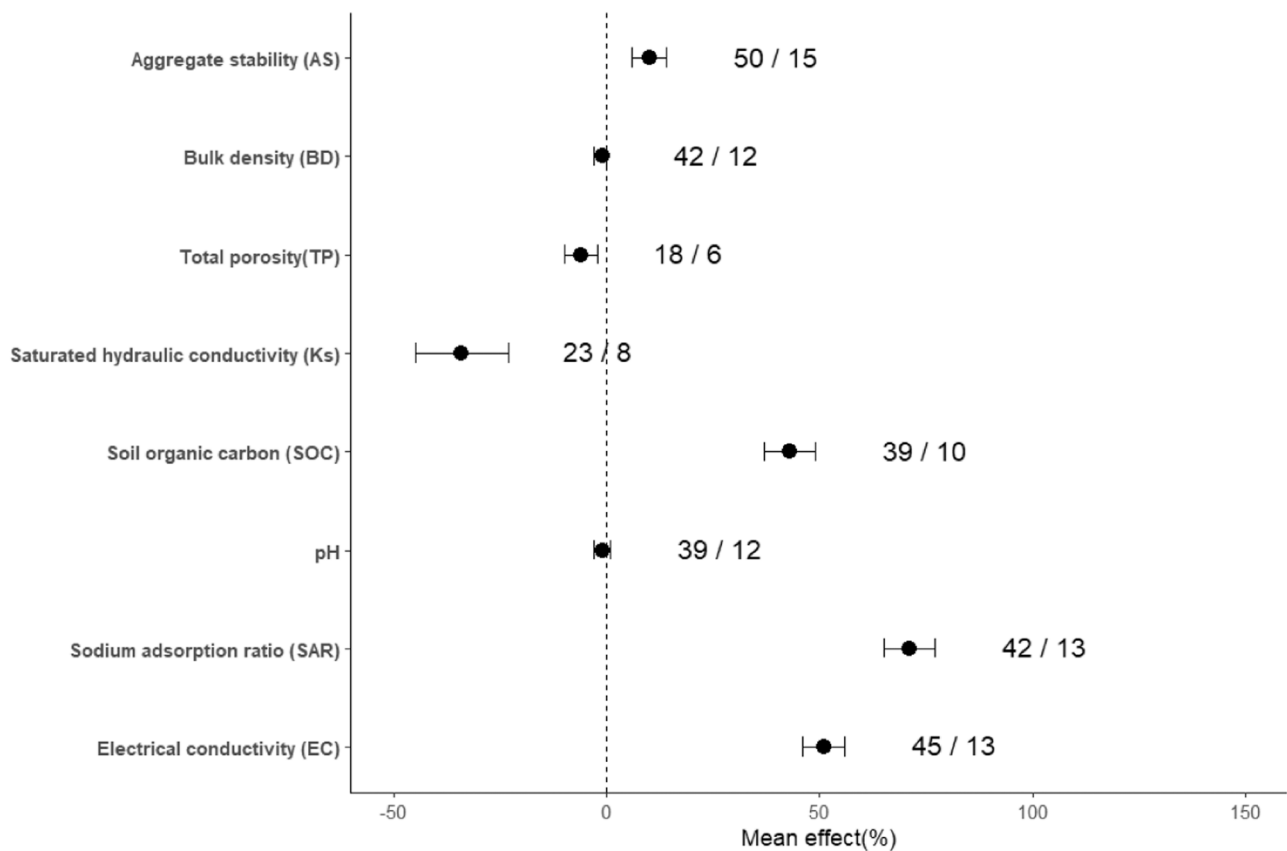


Fig. 2. The overall effect size of each soil indicator represents the treatment (TWW irrigation) relative to the control (conventional water irrigation). The numbers display the total number of observations (left) and the number of publications (right) for each variable. The overall effect was calculated based on a database containing 24 peer-reviewed publications. The length of the error bar represents the 95% confidence interval. The SAR results include data converted from exchangeable sodium percentage (ESP); please refer to the details in the GitHub link.

SAR in cases of repeatable analysis. For publications where only ESP data were available, we converted them to SAR using the commonly-used ESP-SAR relationship from the US Salinity Lab (Richards, 1954), solved for SAR:

$$SAR = \frac{-0.9874ESP - 1.26}{0.01475ESP - 1.475} \quad (1)$$

Within our dataset, where ESP varied between 1.01 and 4.80, this relationship was nearly linear ($R^2=0.9998$, $y = 0.7157x + 0.8101$, with y SAR calculated from Eq. 1, and x ESP). Linearity is needed to transfer standard deviations (SD), which is crucial in meta-analyses for calculating the effect of a given treatment. For a linear equation like $y = x$, the SD is calculated as follows:

$$SD = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad (2)$$

For a linear equation like $y = ax + b$, the new SD can be transferred from the original SD as follows:

$$SD' = aSD \quad (3)$$

The mean, standard deviation, and sample size of eight representative soil indicators (AS, BD, SP, Ks, SOC, pH, SAR and EC) were used to calculate the log response ratio of means (lnRR) as a measure to represent effect size using the Hedges method (Hedges et al., 1999) as follows:

$$\ln RR = \ln \frac{X_T}{X_C} = \ln X_T - \ln X_C \quad (4)$$

Here, X_T and X_C refer to the mean values of the given observation for the treatment (T, with TWW irrigation) and control (C, with

conventional water irrigation), respectively. The different units of the observation do not affect the calculation of the mean effects as they were taken as a ratio. The sampling variances V of the RR were calculated according to Hedges et al. (Hedges et al., 1999):

$$V = \frac{SD_T^2}{n_T X_T^2} + \frac{SD_C^2}{n_C X_C^2} \quad (5)$$

where n_T and n_C , and SD_T and SD_C are the sample sizes (replicated plots of the same treatment or duplicate samples in the same plot) and standard deviations for the experimental and control groups, respectively.

The 95% confidence interval was calculated as:

$$95\%CI = RR_w \pm 1.96\sqrt{V} \quad (6)$$

If the confidence interval does not encompass zero, this indicates a significant effect of the experimental manipulation on the response variable on average, as highlighted by Harrison (2011). This signifies that the experimental intervention has a statistically significant impact on the measured outcome.

All analysis were performed in R.4.1.2 (R Core Team, 2013). The lnRR and V values were calculated in R using the 'ROM' measure in the 'escalc' function with the package 'metafor (version 3.8-1)' (Viechtbauer, 2010). We further displayed the resulting log response ratio as a percentage of change ($\exp^{RRw} - 1$) 100% for easier interpretation.

The finally withdrawn 24 publications were divided in subgroups based on TWW class and soil texture. The classification of TWW into primary, secondary, and tertiary treatment classes, as defined by FAO (AquaStat, 2010), is crucial to understand and predict its impact. In cases where the TWW class was not explicitly reported by the authors, we deduced the classification based on available information about

incoming BOD/COD, and total suspended solids (Aquastat, 2010). Some of the TWW data in the publications were not allocated to a specific class due to insufficient information on the type of TWW used or when multiple types of TWW were employed.

Since different soil textures have different responses to the concentration of soluble salts and specific cations in particular (e.g. Ca²⁺, Na⁺, Mg²⁺,), the data pairs were also grouped into three major texture categories: coarse-textured, medium-textured, and fine-textured soils (Razzaghi et al., 2020). This allowed to gain insights into the specific responses of different soil textures to TWW irrigation. The coarse-textured group consisted of USDA soil textural classes loamy sand and sand, the medium-textured group included loam, sandy loam, silt

loam, sandy clay, and sandy clay loam, while the fine-textured group comprised clay, clay loam, silty clay, silt, and silty clay loam. In some studies where general terms like ‘sandy’ or ‘loamy’ or ‘clayey’ were provided, the soils were put in the appropriate soil textural group. Additionally, we could not classify some soil textures from the papers as they did not mention relevant information on soil texture.

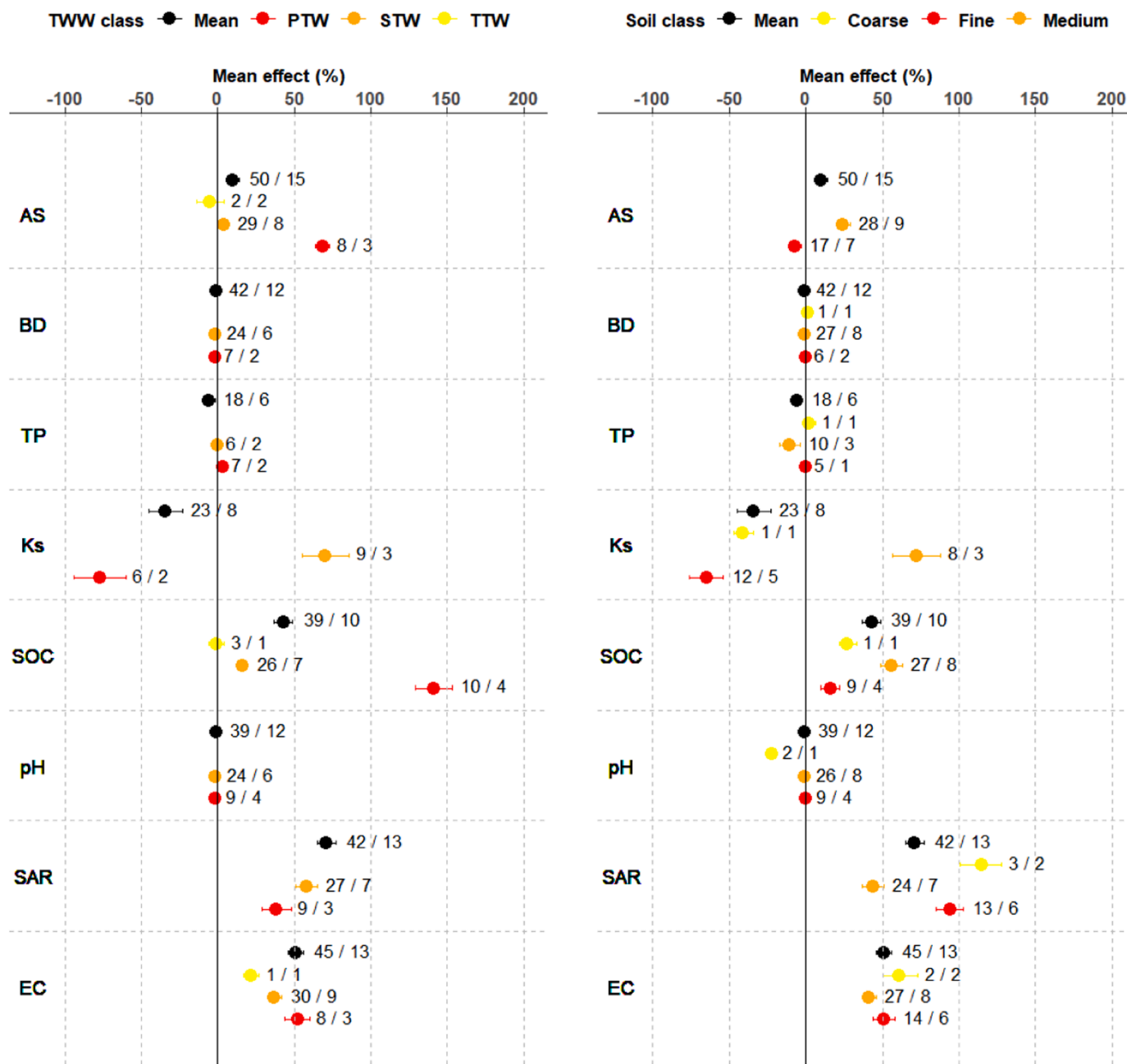


Fig. 3. Mean effect size of the application of treated wastewater with respect to the conventional water irrigation, with values grouped by the treated wastewater classes (left) and soil textures (right) for all soil indicators. The numbers display the total number of observations (left) and the number of publications (right) for each variable. The mean effect was calculated based on a database containing 24 peer-reviewed publications. PTW: Primary treated wastewater, STW: Secondary treated wastewater, TTW: tertiary treated wastewater. Coarse: coarse-textured soil, Fine: fine-textured soil, Medium: medium-textured soil. AS: aggregate stability, BD: bulk density, TP: total porosity, Ks: saturated hydraulic conductivity, SOC: soil organic carbon, and EC: electrical conductivity. The length of the error bar represents the 95% confidence interval. The SAR results include data converted from exchangeable sodium percentage (ESP); please refer to the details in the GitHub link.

3. Results and discussion

3.1. Application of treated wastewater irrigation results in soil salinization and sodification

Fig. 2 shows the impact of TWW irrigation on all assessed soil quality indicators. The results show an increase of TWW irrigation on soil SAR ($71 \pm 6\%$) and EC ($51 \pm 5\%$) compared to conventional water irrigation, indicating that TWW irrigation contributed to soil salinization and sodification. This increase in soil salinity is expected, due to the higher concentration of cations present in TWW, leading to elevated EC levels in soil where those ions accumulate, especially if there is not enough natural or artificial flushing of salts after the growing season. Additionally, the presence of exchangeable sodium cations (Na^+) in TWW irrigation contributes to higher SAR, which are indicators of soil sodicity and therefore point out a risk of structural degradation in the longer term (Gao et al., 2021; Schacht and Marschner, 2015).

Fig. 3 shows that these average effects were different when considering the degree of TWW treatment. Both primary TWW (EC: $52 \pm 8\%$ and SAR: $38 \pm 10\%$) and secondary TWW (EC: $37 \pm 4\%$ and SAR: $58 \pm 7\%$) exhibited higher salt accumulation than tertiary TWW irrigation. This observation aligns with the findings of a meta-analysis conducted by Gao et al. (2021), who reported the greatest accumulation of salt in primary TWW irrigation compared to secondary and tertiary TWW irrigation. This is logical, since the level of treatment and filtering steps applied to the TWW affect the presence of salts in the TWW and subsequently the degree of soil salinization.

Among the different soil texture categories, coarse-textured soils exhibited the highest increase in EC by $61 \pm 11\%$, indicating a higher accumulation of salts (Fig. 3). This might be counter-intuitive, since coarse-textured soils typically have larger pore spaces, allowing for better water movement and supposedly reduced retention of salts and pollutants compared to fine-textured soils (Hillel, 2003; Bouman et al., 2007). Nevertheless, this could result from more water being applied to this soil type during an irrigation event and therefore also more salts. It should be noted though that this finding is based on two observations from one publication only. Furthermore, it is crucial to acknowledge that the highest increase in SAR ($115 \pm 14\%$) among the soil textures for coarse-textured soils is derived from just two publications, which may not be sufficient to draw definitive conclusions and discussions. On the other hand, fine-textured soils, based on 13 observations from six publications, showed a higher SAR ($94 \pm 9\%$) compared to medium-textured (with 24 observations within seven publications). Clay particles have a high cation exchange capacity, which makes them more prone to exchanging sodium ions from the TWW, leading to higher sodicity (Gharaibeh et al., 2016). Our analysis suggests that TWW usage can lead to increased salinity and sodicity in all soils compared to conventional irrigation. Moreover, the magnitude of these effects may vary based on soil texture, as soil texture affects the retention rate of the main salt-base ions.

Fig. 2 demonstrates that the mean effect of TWW irrigation on soil pH was not significantly different from that of conventional irrigation. A change in soil pH can occur, but this change is counteracted by addition of CaCO_3 through the TWW (Daliakopoulos et al., 2016; Tsigoida and Argyrokastritis, 2020). However, there was insufficient data available on soil CaCO_3 content in the publications analyzed in this study, making it difficult to statistically analyze its response to TWW irrigation. When splitting up the dataset into soil texture categories (Fig. 3), it becomes clear that the pH of coarse-textured soil decreased significantly by $22 \pm 2\%$ upon TWW irrigation as compared with conventional irrigation, while that of fine- and medium-textured soil remained unchanged. This decrease in soil pH of coarse-textured soil is supported though by only two observations across one publication (Appendix A) But, this result aligns with Bedbabis et al. (2014), who reported similar observations in coarse sandy soils when comparing TWW to freshwater irrigation. The decrease is likely due to: (i) absorption of ammonia ions by plants or

nitrification of ammonium, and (ii) leaching of basic cations (Tarchouna et al., 2010). Some researchers (Ibrahimi et al., 2022; Singh and Agrawal, 2012) argued that the lower pH in TWW-irrigated soils results from higher rates of nitrification, leading to the release of free hydrogen. Additionally, the increase of soil EC/SAR may further enhance the leaching of basic cations, contributing to the observed decrease in soil pH with depth. When EC/SAR levels are elevated, an excess of exchangeable sodium ions (Na^+) is present on the soil exchange complex. These sodium ions can displace other cations, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), from soil colloids through ion exchange processes. As a consequence, these displaced cations are more prone to leaching downward with water movement (Jalali et al., 2008). The leaching of basic cations (Ca^{2+} and Mg^{2+}) and the accumulation of Na^+ can lead to an alteration in the soil's pH. Sodium ions are less effective in neutralizing acidity compared to Ca^{2+} and Mg^{2+} , contributing to a decrease in soil pH. Although studies by Tarchouna et al. (2010) and Bedbabis et al. (2014) indicated a change in soil pH for coarse-textured soils following TWW irrigation, the underlying reasons for differences among fine-, medium-, and coarse-textured soils remain unclear.

3.2. Effects of treated wastewater irrigation on soil structure are inconclusive

The application of TWW led to a significant increase in AS by $10 \pm 4\%$ and SOC by $43 \pm 6\%$ (Fig. 2). The observed increase in aggregate stability is consistent with previous research (Cakmakci and Sahin, 2021). However, there are also articles reporting in contrast a reduction in water-stable soil aggregates in the soil layers of (Morugan-Coronado et al., 2011), 0–10 cm (Schacht and Marschner, 2015), and 0–90 cm with spreads of 30 cm (Paudel et al., 2018). The observed increase in SOC can contribute to enhanced soil structural stability, explaining a rise in aggregate stability. This corroborates the findings of Cakmakci and Sahin (2021) and Bedbabis et al. (2015), who observed that the high concentrations of BOD and COD in TWW leads to an increase in soil organic matter, further supporting the increase in aggregate stability. However, the increase in SOC might also lead to a decrease in soil BD (Cakmakci and Sahin, 2021). It is worth noting that while this meta-analysis found a decreasing trend in BD ($-1 \pm 1\%$), this change might differ after long-term TWW irrigation, as most field experiments included in the analysis were conducted over a period of less than 5 years.

The response of soil structure related indicators to TWW irrigation varied based on the wastewater treatment classification (Fig. 3). For instance, primary TWW exhibited a significant increase in SOC ($141 \pm 12\%$) and AS ($69 \pm 4\%$), while secondary TWW showed a smaller increase in SOC ($16 \pm 3\%$) and AS ($4 \pm 3\%$), and tertiary TWW showed no significant change. The decrease in total suspended solids in tertiary TWW after advanced TWW treatment might explain the limited change in SOC after its application. The increase in SOC can also be attributed to dissolved carbon in TWW, particularly in primary TWW, which retains a higher percentage of total suspended solids, and oil and grease (Aqua-stat, 2010). With soil aggregation being the nucleus of all mechanisms of soil carbon sequestration (Blanco-Canqui and Lal, 2004), stable soil aggregates created with the assistance of SOC derived from TWW might result in more efficient carbon sequestration.

Regarding soil texture classes, the application of TWW led to a significant increase in SOC in both fine-textured and coarse-textured soils, with a rise of $16 \pm 6\%$ and $27 \pm 5\%$, respectively, aligning with previous research (Rezapour and Samadi, 2011). It should be noted though that in our database, SOC was only considered in one publication with coarse-textured soils and four publications with fine-textured soils. In fine-textured soils, aggregate stability decreased by $-7 \pm 4\%$, which may be related to the adverse effects of high sodicity and the presence of humic substances in the TWW (Levy, 2011). In contrast, medium-textured soils (with 27 observations within seven publications) exhibited a more substantial increase in SOC ($56 \pm 7\%$) and AS ($24 \pm$

4%) after TWW irrigation, highlighting the potential benefits of TWW application in such soils.

In some conditions (Tunc and Sahin, 2015), it was observed that BD decreased less under TWW irrigation conditions compared to freshwater irrigation. Additionally, after irrigation with both fresh water and TWW, BD was found to be higher in two soil layers compared to the trail irrigated with solely TWW. This indicates that changes in BD are not only affected by the type of water, but also by the process of irrigation itself. Structuring effects of TWW occur slowly, and more detailed analyses of pore size distribution are needed to fully understand specific changes within the pore systems for future TWW irrigation research (Leuther et al., 2019; Cakmakci and Sahin, 2021). Understanding the long-term effects of TWW irrigation on soil structure is crucial for sustainable agricultural practices and efficient water resource management.

3.3. Saturated hydraulic conductivity is generally reduced upon treated wastewater irrigation

Although the impact on indicators for soil structure is not clear, Fig. 2 reveals a significant decrease in soil Ks by $-34 \pm 11\%$ after TWW irrigation compared to conventional irrigation. The reduction in Ks can be attributed to two main factors. Firstly, the high SAR resulting from TWW irrigation causes dispersion of clay particles, leading to a reduction in Ks (Bedbabis et al., 2014). This is clearly visible for fine-textured soils, which exhibit a decrease in Ks by $-65 \pm 11\%$ (based on 12 observations from five publications), accompanied by the highest increase SAR with $71 \pm 6\%$ (based on 13 observations from six publications). Secondly, the presence of suspended solids and dissolved organic matter in TWW irrigation can result in clogging of pores, further reducing Ks (Lado and Ben-Hur, 2010). Furthermore, soil structure is significantly influenced by soil biota (Oades, 1993), and the quality and quantity of organic matter in irrigation water can shape the structure of soil biological communities (Ibekwe et al., 2018). Consequently, organic compounds introduced through TWW irrigation are expected to impact soil structure and, in turn, soil water dynamics. However, the structuring effects of TWW manifest gradually, again necessitating more detailed analyses of pore size distribution to fully comprehend the specific changes within the pore systems for future TWW irrigation research (Leuther et al., 2019; Cakmakci and Sahin, 2021).

While this meta-analysis did not extensively investigate water repellency and infiltration rate due to limited observations in the selected publications, it is expected that TWW irrigation may increase water repellency (Leuther et al., 2019). Adsorption of soluble organic molecules on soil particles can lead to hydrophobicity, further contributing to the decrease in infiltration (Gharaibeh et al., 2016; Leuther et al., 2019). Water repellency may not be a noticeable problem for water dynamics as long as the soil is kept moist, while its effect on water infiltration is more pronounced when soil is dry. Once soil is exposed to water shortage, the risk of preferential flow, surface run-off, and reduced water storage increases severely (Leuther et al., 2019). Water infiltration and soil water repellency are important factors influencing soil hydraulic properties, and future research should prioritize the investigation of these aspects to gain a more comprehensive understanding of the effects of TWW irrigation on soil and plant water dynamics.

When examining the influence of TWW classes on soil hydraulic properties (Fig. 3), although the overall mean effect is a decrease of Ks, an opposite trend (increasing Ks) for secondary TWW irrigation ($70 \pm 15\%$) can be seen, which requires further exploration to understand the underlying mechanisms. In terms of texture, medium-textured soils are the exception, showing a positive effect on Ks with an increase of $72 \pm 15\%$, suggesting that they may be more suitable for TWW irrigation than fine- and coarse-textured soils, as also mentioned by Anane et al. (2012). Further research is needed to understand the complex interactions between TWW irrigation and soil hydraulic properties.

3.4. Limits and perspectives

This meta-analysis employed strict criteria (Fig. 1) to ensure the validity of the selected studies. However, it is important to acknowledge that certain factors that could potentially influence soil hydraulic properties and structure were not considered due to the limited number of eligible publications and observations. For instance, properties of TWW such as the presence of organic compounds, which can induce changes in soil hydrophobicity after application, and the presence of microbial life that might form biofilms, amongst other factors, can impact soil structure and hydraulic properties (Dosoretz et al., 2010). Additionally, only peer-reviewed English articles were included in this meta-analysis. Despite efforts to include Chinese, Dutch and French publications, it was found that Chinese records primarily did not focus on field experiments, Dutch books and articles focused on the purification process and economic feasibility of TWW without specific data pairs needed to meet this paper's requirements, and French records mainly consisted of theses, which were not within the scope of this meta-analysis. Nonetheless, valuable information from these sources was incorporated into the introduction and discussion sections.

To gain a more comprehensive understanding of the effects of TWW irrigation on soil hydraulic properties and structure, future research should explore additional variables and conduct further analyses beyond the scope of this paper. For example, more observations and data on tertiary TWW irrigation are needed to better understand which treatment steps are crucial for sustainable use of TWW in agriculture and horticulture. No data pairs of aggregate stability in coarse-textured soils were available in this study. Therefore, future research needs to work on it.

Generally, studies vary a lot in experimental design, reported data and used methods, which makes a quantitative comparison challenging. In addition, studies should mention standard deviation or standard error of acquired data instead of only displaying for example infiltration rate curves. Moreover, detailed information on quantities of the composition and amounts of TWW applied is often lacking, but is crucial to understand underlying mechanisms for the observed effects. At the moment, we were only able to distinguish different levels of quality of applied TWW, but could not assess the quantities of, for example, total suspended solids/SOC/EC and relate them to soil indicators (e.g., Ks/AS/EC). In addition, more accurate information on timing of sampling and impact of natural precipitation events on the soil water and solute balance is required to investigate the impact of TWW on soil hydraulic and physio-chemical properties. For instance, evaporation losses can range from 50% to 90% in arid regions resulting in 2- to 20-fold increases in soluble salts (Adhikari et al., 2011) for the same amount of irrigation water applied. Also, the irrigation dosage and frequency create wetting and drying cycles in the soil, which represent critical natural processes influencing the structural stability of the soil (Morugán-Coronado et al., 2011). Particularly in poorly structured soils, cyclic wetting and drying can contribute to the degradation of the soil surface (Wagner et al., 2007). Although most reviewed publications used freshwater irrigation, some compared rainfed with TWW-irrigated agriculture, introducing agricultural intensity as an additional factor. This means that differences observed might stem from intensity levels, and not water quality alone. However, our data lacks clear evidence of this distinction, highlighting the need for further research. More standardized, preferably long-term studies with accurate and complete metadata would open a venue of valuable insights into the underlying mechanisms that govern the effects of TWW irrigation on soil properties.

4. Summary and conclusions

Irrigation with TWW significantly increases soil salinity and sodicity, as indicated by the mean effect of EC and SAR, through the addition of external salts to the soil with the TWW. Primary TWW, which is only marginally filtered, still contains many suspended and dissolved solids

and has a high carbon content, which leads to a noteworthy increase in SOC and improves AS. Nevertheless, the accumulation of organic materials in the soil negatively impacts its permeability and reduces Ks. Interestingly, secondary TWW irrigation has less impact on soil structure, probably due to a lower contribution of SOC from the TWW, resulting in fewer changes in AS. Surprisingly, Ks even increased after secondary TWW irrigation, which warrants further investigation. In fine-textured soil, the salinity and sodicity result in clay dispersion and pore clogging by clay migration, reducing soil Ks. The effect on BD, TP, and pH was small, suggesting that the total soil pore space and pH did not undergo substantial changes after TWW irrigation. Overall, we saw a soil-type effect of TWW application on Ks, AC, SOC, SAR and EC. Although the number of peer-reviewed publications that met the requirements of our meta-analysis was to 24, our analysis at least indicates that different soil types respond differently to TWW application. To better understand the impact of TWW irrigation and the role of soil type on physical soil quality, there is an urgent need for more and better standardized (long-term) field experiments across various pedo-climatic conditions and with clear information on the composition of the applied irrigation water.

CRedit authorship contribution statement

Wim Cornelis: Writing – review & editing, Supervision. **Sarah Garré:** Writing – review & editing, Supervision. **Lin Wang:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Guillaume Blanchy:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data as well as the R scripts used to generate the results reported in this study are available at <https://github.com/linwang-tech/Meta>.

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Appendix A

Appendix A gives an overview of the studies for this meta-analysis. Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2024.108752](https://doi.org/10.1016/j.agwat.2024.108752).

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